Dealing with plant phenotypic plasticity using FSPM: Opportunities and challenges for plant breeding

The rice example

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French-Brazilian Meeting on Functional-Structural Plant Modeling (FSPM). 1, 2011/10/24-27, Campinas, Brazil

Talk structure

1. Novel challenges in plant breeding
    - Climate change, bio-energy crops, use of novel molecular tools
2. Role for FSPM
    - Phenotyping : identify relevant traits to explore genetic bases
    - Ideotyping : seek for relevant trait combinations (performance)
    - Opportunities, challenges: Ecomeristem model example (rice)
3. Conclusions & perspectives
    - Next challenges for FSPM in this context?

Context: Novel breeding challenges

- **Green revolution** (80's): yield potential & system intensified

⇒ Genotype (G) adaptability to environment (E) neglected

- **Climate change issues**: need to improve plant adaptability to increasingly fluctuating climate

- **Novel challenge**: combine adaptability & yield potential

⇨ **Targeted plant ideotypes (ideal genotypes) more and more sophisticated**

Need for plant phenotypic plasticity

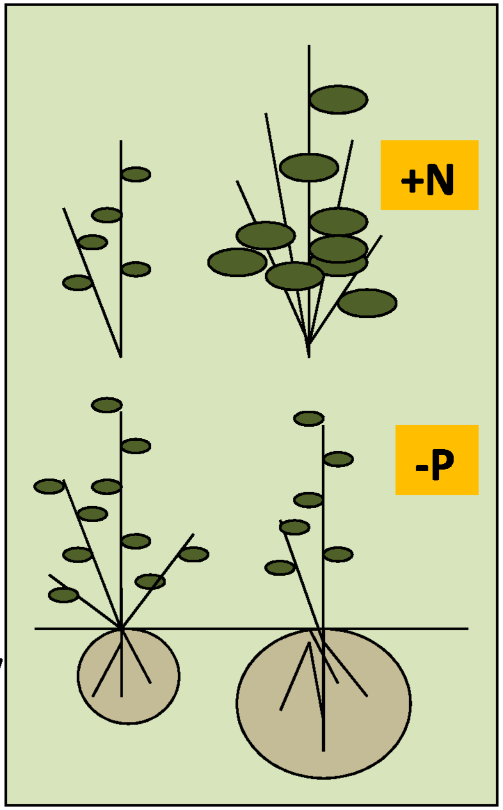
Capacity to dynamically regulate morphogenesis

(Nicotra *et al.* 2010)

– Favor the growth of organs facing the constraint and stay alive (ecological point of view)

– **Maintain yield (breeding point of view)**

– Includes more than morphology: phenology, physiological defenses… **Functional & structural traits!**



Examples of traits needed under increasing climatic variability *(cereals)*

Phenology

- Rapid early development (vegetative) : competition against weeds

Morphology

- Architecture maximizing resource use efficiency

Physiology

-Protection of reproductive processes (e.g. cooling of inflorescence to avoid sterility)

Context: Novel breeding challenges

- Ideotype complexity amplified by the objective of multipurpose crops (food/fuel/feed)

- **Ideotypes must gather traits rarely combined in existing natural diversity (sometimes negatively linked)**

Multi purpose
(eg. grain, biomass, sugar)

Adaptability, plasticity
and yield stability

Context: recent advances of molecular breeding

- Genomes of several species sequenced (rice, sorghum…)
- Seek for molecular markers controlling traits of interest
- Use marker combination to accelerate breeding

  => Marker assisted selection

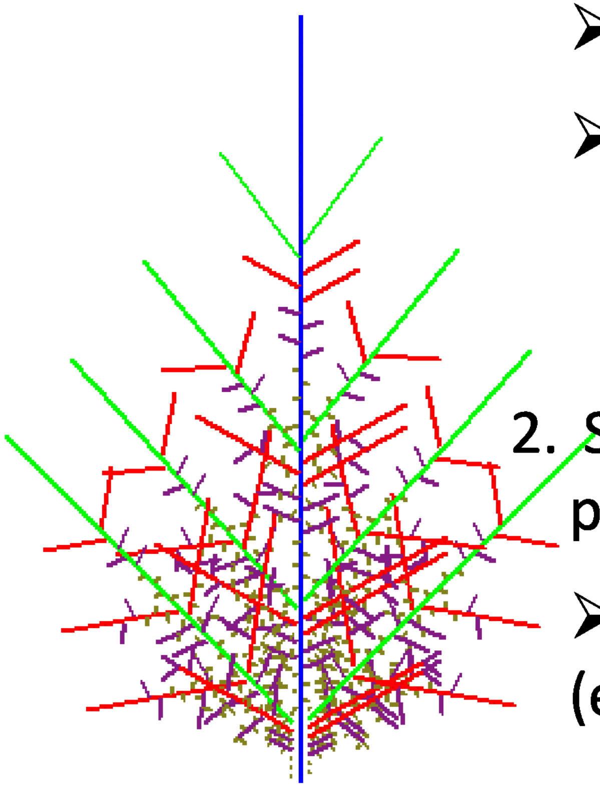
- Technically possible but…

Context: current limits to molecular breeding

- Ideotypes increasingly complex (genetically, physiologically)
  - ⇨ First need to relate component traits to genetic markers
  - ⇨ Then test the physiological & genetic relevance of trait combination
  - ⇨ As traits are not necessarily independent (genetic, physiology)

Prior to create ideotype, its physiological & genetic pattern must be understood

Issue: linkage between traits regulating whole plant morphogenesis



1. Growing organs (sink) depend on meristem activity
   - Organ initiation, size, expansion …
   - Some genetically linked (trade-off)
     (eg. Leaf size vs number; Tisné et al. 2008)

2. Sinks in the plant compete for the same resource pool: physiologically linked
   - Trade-off for resource allocation and growth
   (eg. branching vs. organ size; Rebolledo et al. 2011)

Plant system complexity

How FSPM can help?

1. Formalize knowledge on a complex system: plant morphogenesis
   component traits linkages & integrated impact on performance
2. Identify most impacting component traits (for genetic study)
3. Use parameters of single equations separating G and E effects as traits closer to genetics **(relevant for phenotyping)**
4. Test hypotheses (trait combination: **ideotyping)**

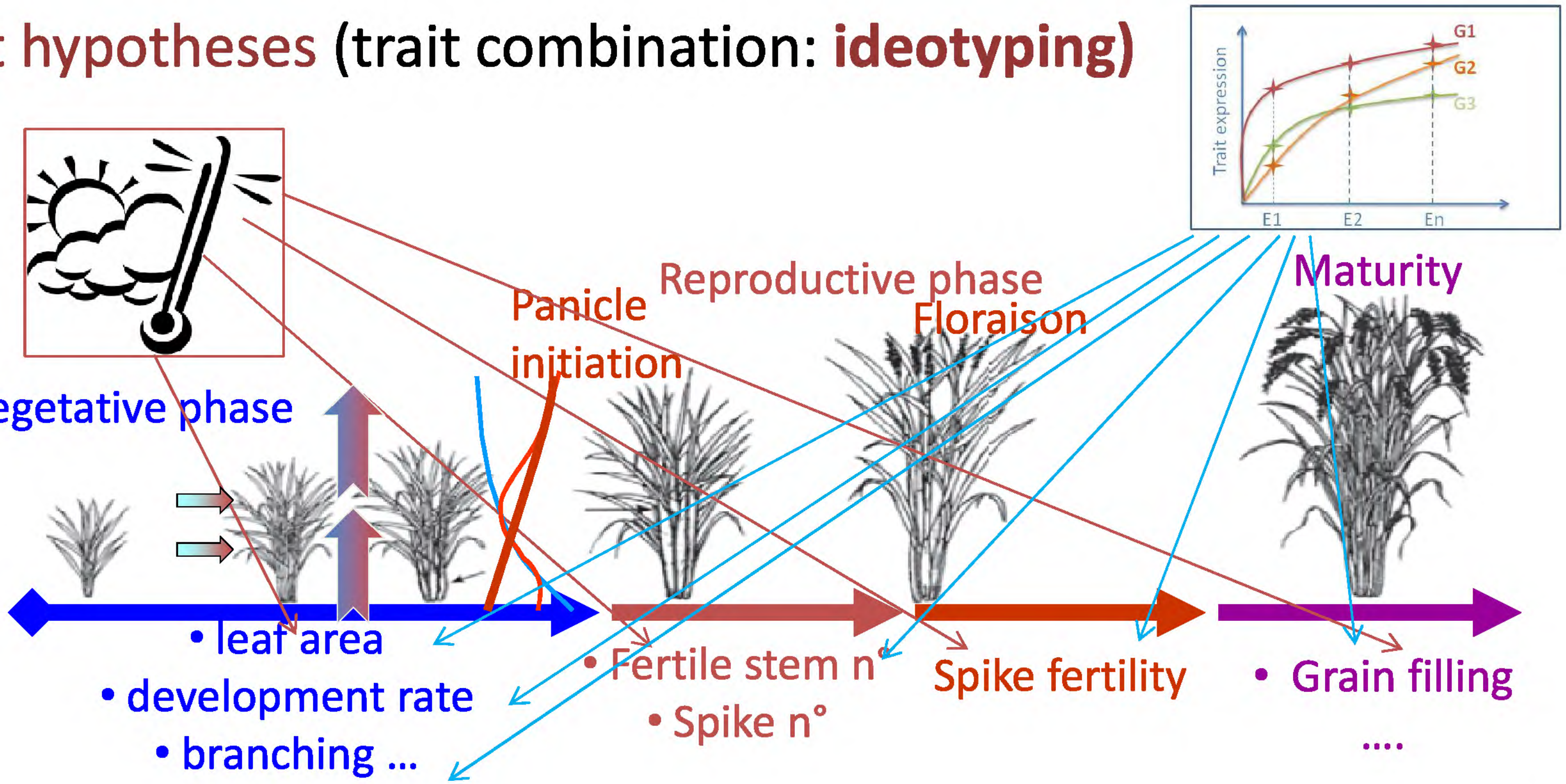
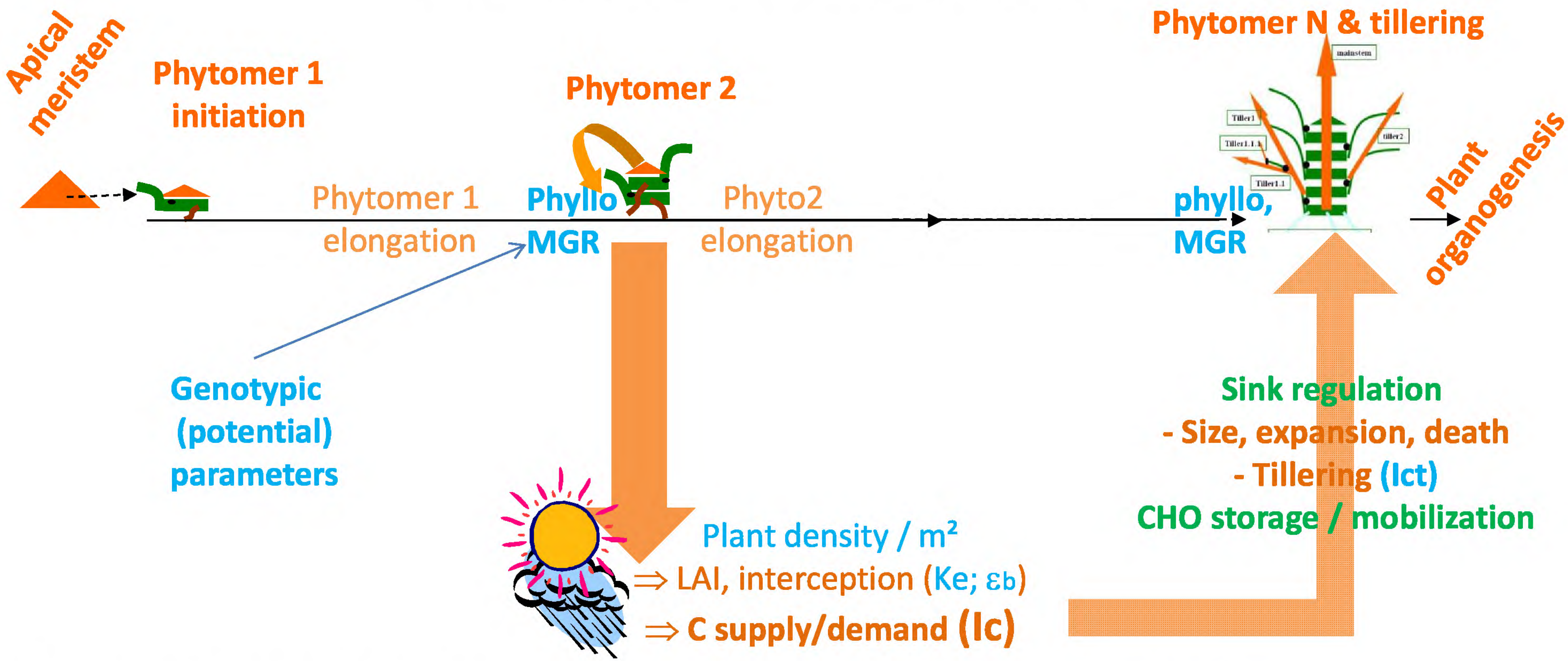


Illustration:

Using Ecomeristem a model of plant vegetative morphogenesis to support rice phenotyping and ideotyping

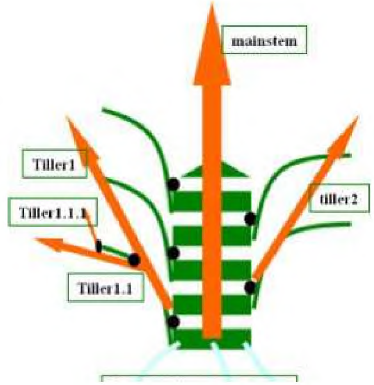
Ecomeristem model: Main concepts

Model simulating **plant vegetative morphogenesis and its plasticity** in the population at daily time step



- Phenotypic plasticity simulated (topology but is geometry optional)
- Using Ic as a proxy of sugar signaling & parameter for G potential or response to E
- Regulating organ sizing, senescence, tilleringC storage/mobilisation
- Roots only a bulk biomass compartment (proportional to daily shoot demand)

Ecomeristem inputs / outputs

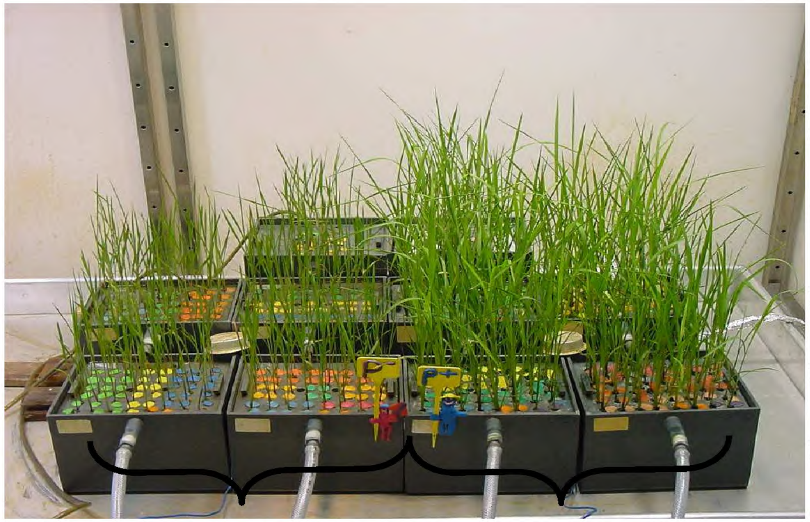


- Daily inputs: Radiation, air T°, ET0, water supply
- Daily outputs: plant topology
- Organ rank, age, size, biomass, status (source, sink, dead) => per plant & m^2
- ~20 plant parameters, with 6-8 genotype dependent
- Model validated for different G &E (drought, Luquet et al. 2006, 2008, 2011)
- Coded in Delphi (object oriented)
- Coupled with tools for sensitivity analysis, optimization
- Coupled to 3D models (OpenAlea platform, session 5)

(nb: model also applied for sorghum, sugarcane)

Ecomeristem to support phenotyping

Challenge: use source and sink model parameters
Case of rice vegetative plasticity under P deficiency



P No P

- Growth chamber hydroponics
- 180 genotypes (lines)
- 24 days, 3 reps, 2 treatments (P / No P)

⇒ Biomass (shoot, root)

⇒Tiller and leaf number

⇒ Youngest expanded leaf size

Model calibration (parameter value) for each genotype:

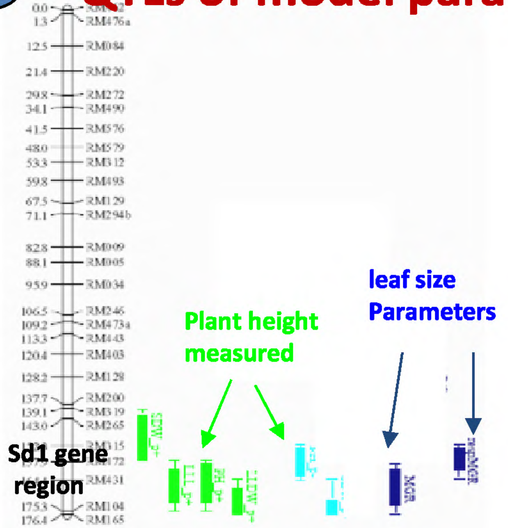
- **MGR** (Meristem Growth Rate: potential organ sizing)
- **Ict** (tillering sensitivity to Ic = C supply / demand)
- **R/S** (biomass allocation to root vs shoot)
- Phyllochron (**PHYLLO**)

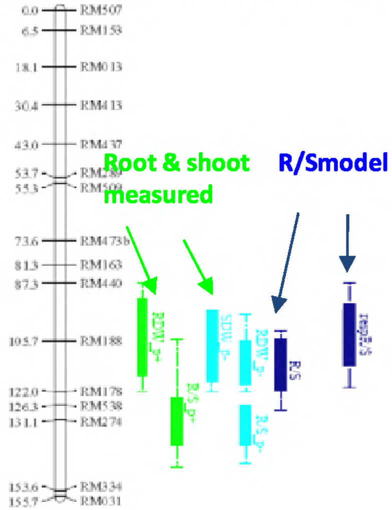
  & corresponding response parameters to P deficiency

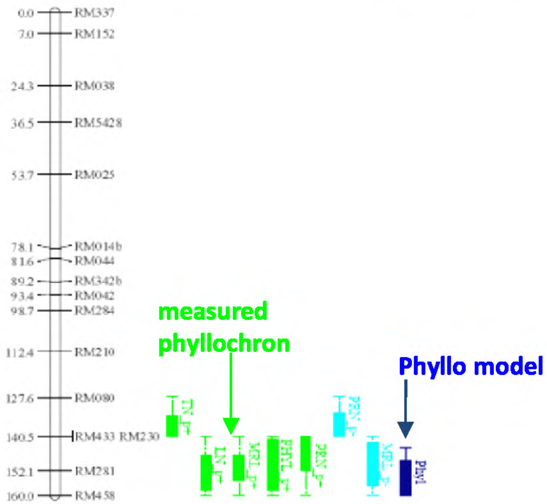
QTLs detected by model parameters: examples

(Ahmadi et al. 2008)

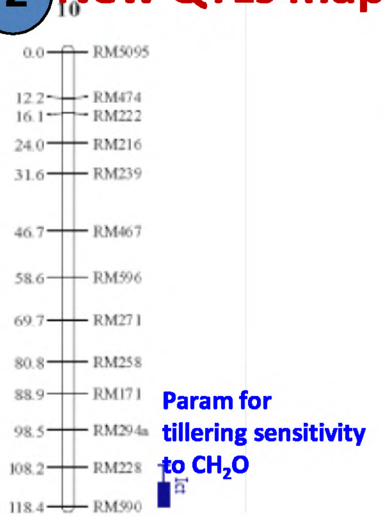
1 QTLs of model parameters confirm QTLs of measured traits (meaningful)







2 New QTLs mapped by model parameters…



Model relevance to dissect genetic bases of whole plant morphogenesis and plasticity?

⇒ **Preliminary results**

⇒ **Currently confirmed (rice under drought)**

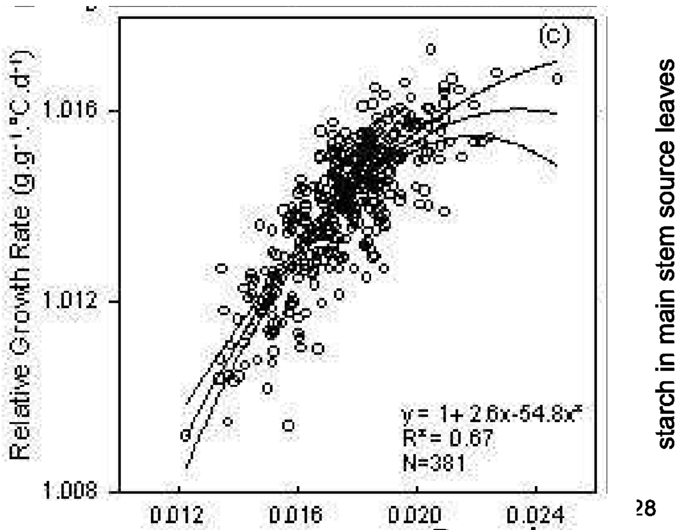
Ecomeristem to explore virtual genotypes (ideotyping)
How Development Rate determines rice early vigor?

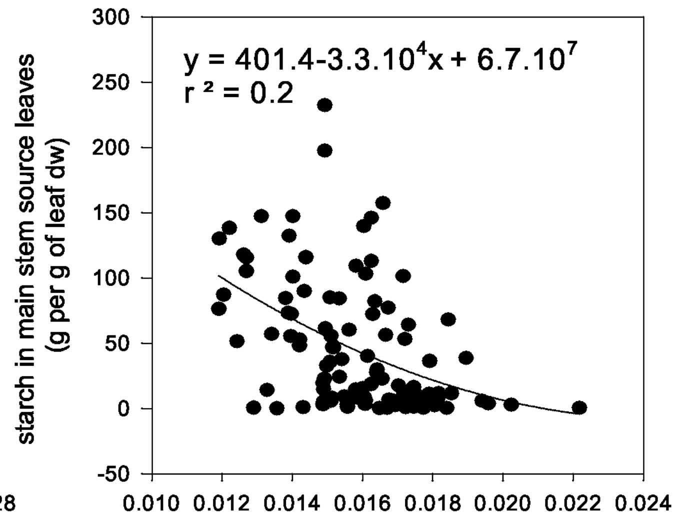
DR: leaf production rate (1/phyllochron)

Early vigor: vegetative growth rate (++ resource acquisition, competitiveness (weeds)

Experimental starting point (200 rice genotypes):

$\Rightarrow$ **DR main driver of** early vigor (RGR) associated with **low starch storage**





Development Rate (°Cd^{-1})

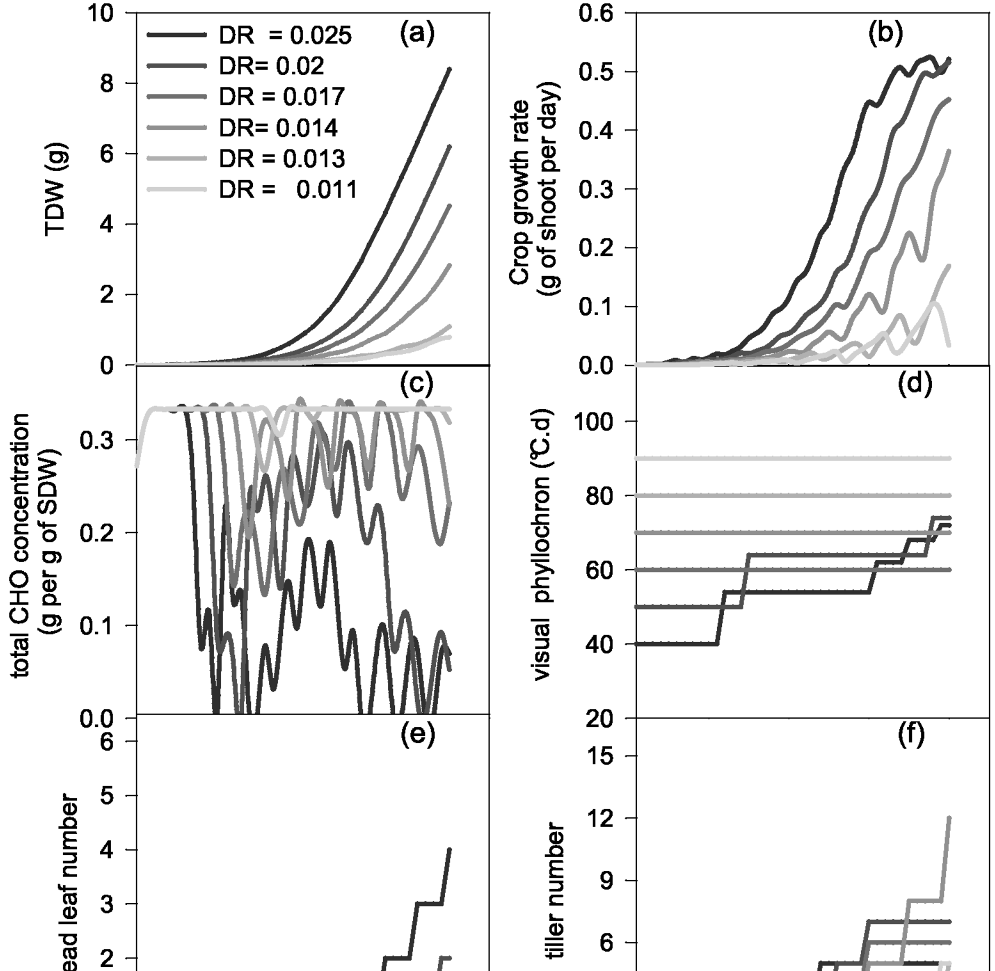
Question: Bold (no C storage, high DR) vs. conservative (C storage, low DR) ?

$\Leftrightarrow$ **Which C source-sink relations behind these behaviors**?

$\Leftrightarrow$ **How to optimize early vigor?**

Ecomeristem to explore virtual genotypes (ideotyping)
C Source-sink processes underlying DR effect on early vigour

(Luquet et al. 2011)



6 DR values, other parameters constant (40 day simulations)

Rapid DR increases…

⇒ growth rate

⇒ transitory reserve depletion

⇒ tillering

But can also cause « **nutritional crisis** »

⇒ delayed leaf appearance

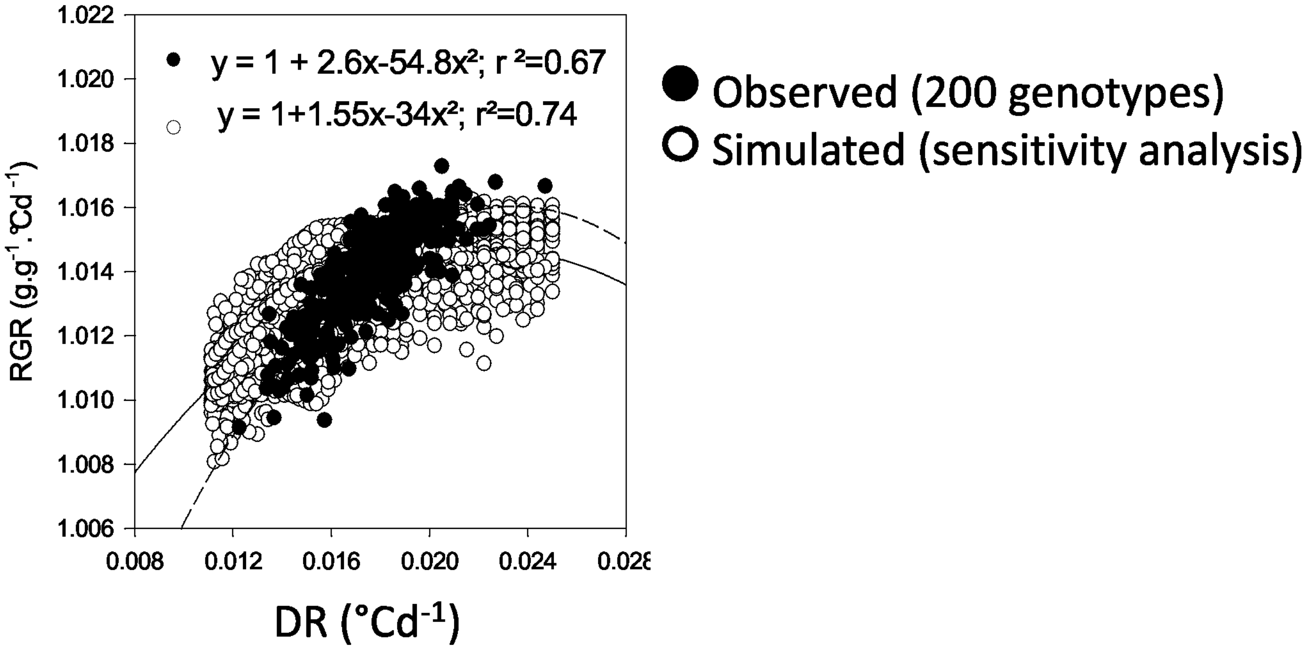
⇒ smaller leaves

⇒ accelerated leaf senescence

DR favors vigor - ideally combined with starch storage
(observed on genotypes with large leaves… traits to be combined)
NB: improves recovery after a drought event

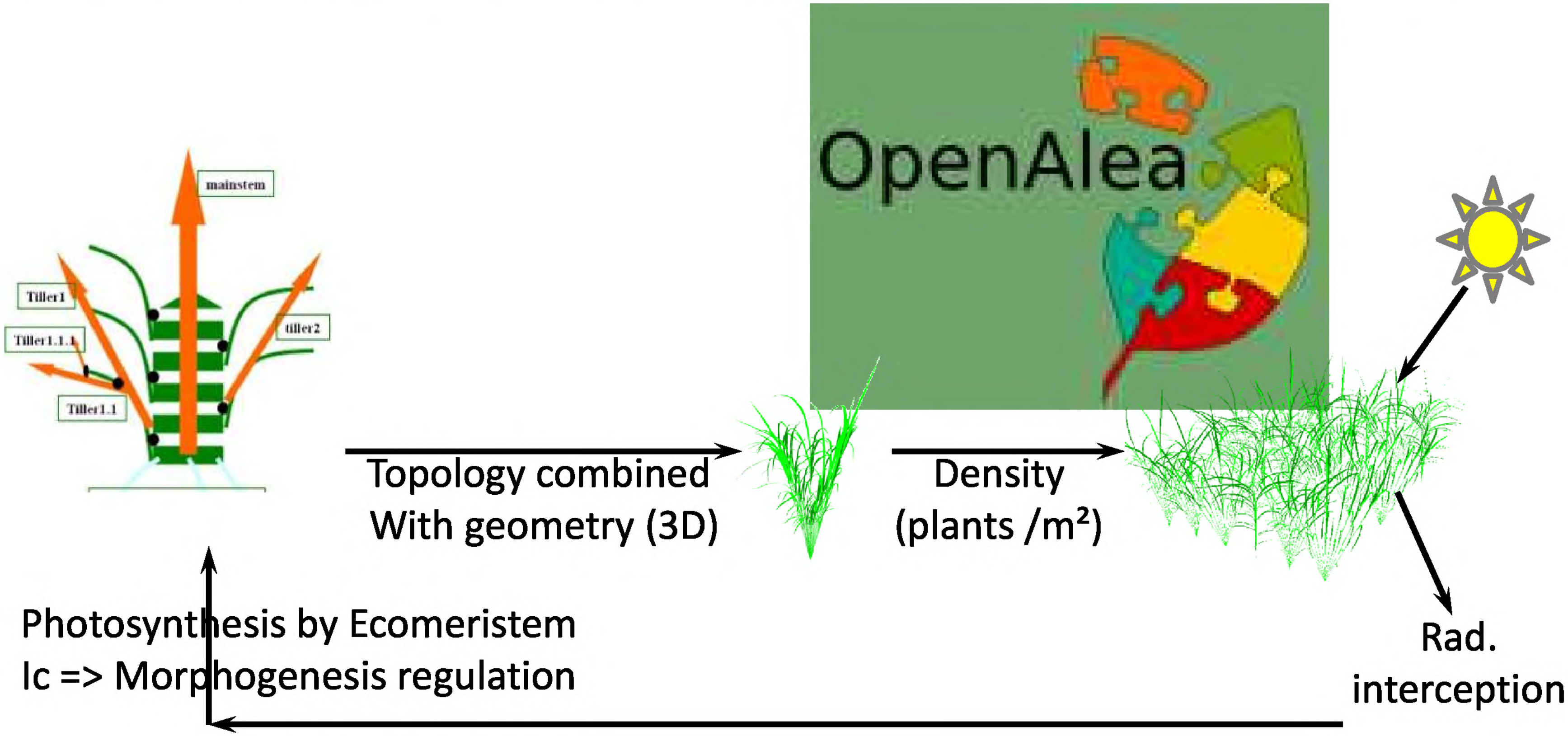
Ecomeristem simulates the linkage between traits observed in natural genetic diversity (200 genotypes)

Model sensitivity analysis (RGR simulated for wide ranges of parameters)
Same environmental conditions as for observed 200 genotypes



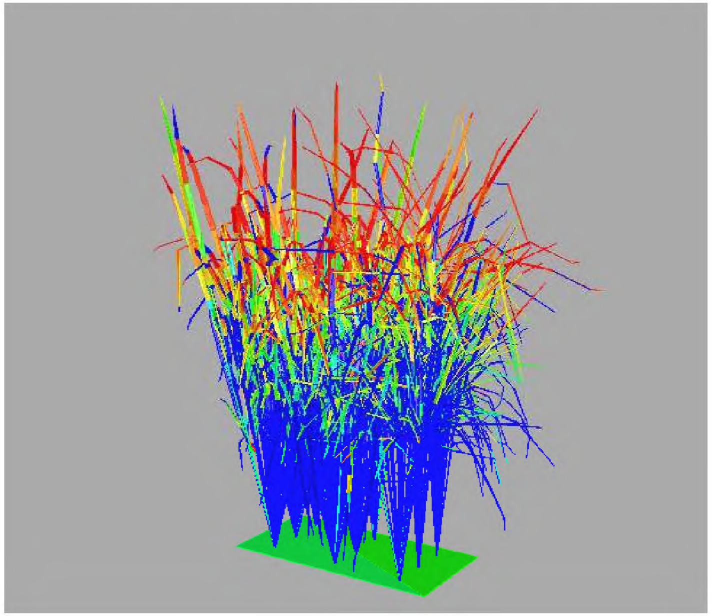
Combining Ecomeristem with 3D modeling
(Soulie et al 2010)

- Objective: account for architectural traits in ideotyping
- Combine topology with 3D info
- Limits: simulation duration & needs geometrical data
- Powerful exploratory tool, not suited for all applications (heavy)

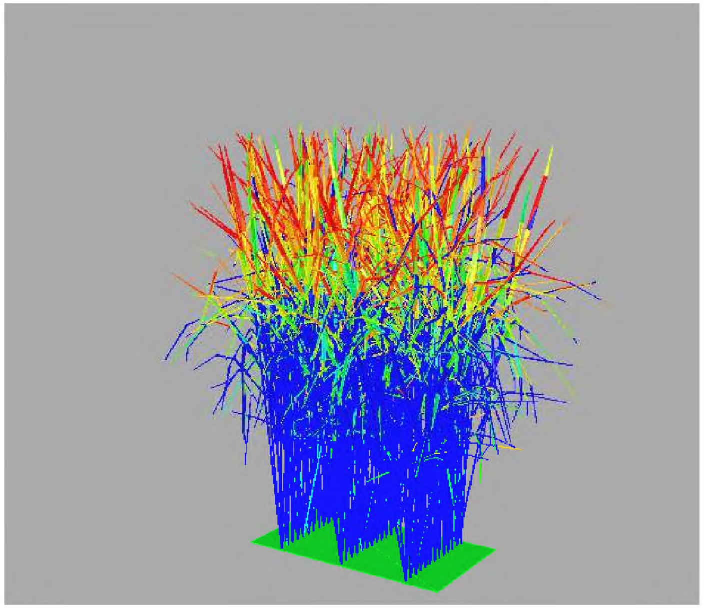


3) 'Ecomeristem-3D': visualizing plasticity and considering architectural traits to compute radiation interception

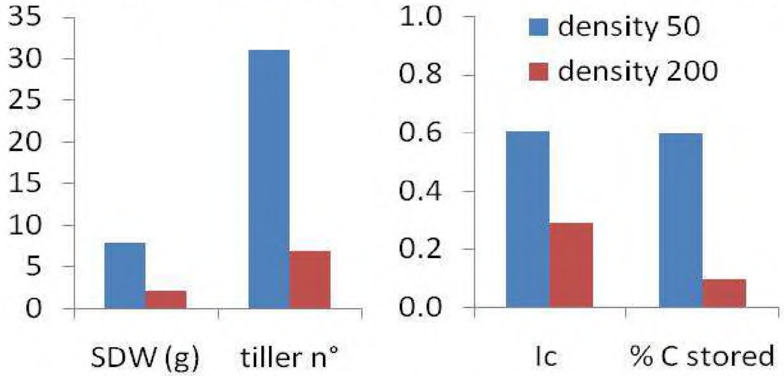
Plant density : 50 / m²



Plant density : 200 / m²



Corresponding variables simulated 40d after germination



Conclusions & Perspectives

- FSPM powerful to formalize physiological & genetic linkages among traits in plant system: GxE, phenotypic plasticity
- Support experimental (in vivo) studies and breeding
- Ideotyping and phenotyping
- integrate genetic information (parameters related to QTL effects)
- But complex tools: time, parameter number (calibration, validation)
- Need for simplified versions to apply concepts for ≠ applications

Conclusions & Perspectives

- Ecomeristem relevance for analysing source-sink relations : ideotyping
- Ecomeristem (parameters) application to phenotyping still explored

  (at least advice on traits for phenotyping)

- Ongoing improvements of Ecomeristem:
  - Extend concepts to the reproductive phase (yield formation)
  - Improve feedback with 3D using OpenAlea platform (photosynthesis, energy balance, organ response to CO2 and T°)
  - Enhance the formalization of trait linkages, integrate genetic information and explore ideotypes